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407-5

Cr 53 025

N64-80398

Code none

Technical Report No. 32-139

Thermal Radiation in Gaseous Fission Reactors for Propulsion

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July 24, 1961

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

$\boxed{2}$ (NASA CONTRACT ~~No.~~ NASw-6)

(NASA CR-53025; JPL-TR-32-139)

~~Technical Report No~~. (TR-32-139); NASA CR-53025)

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ABSTRACT

The influence of thermal radiation, produced by the fuel-propellant mixture in the cavities of a gaseous fission reactor, on the specific impulse, engine specific weight and solid fuel loading requirements is examined. An attempt is made to bracket the actual radiative properties of the mixture by considering two limiting cases, an opaque and a transparent gas. In obtaining the total power balance in the engine, an enthalpy-temperature relation is selected which is appropriate for hydrogen propellant.

The analysis indicates that in the booster application of gaseous reactors, the choice between an opaque and a transparent gas is not critical to the determination of engine performance. The choice is critical, however, in systems of low thrust and very high specific impulse, and the opaque gas yields lower specific engine weights.

I. INTRODUCTION

It has been shown that the energy deposition rate in the solid members of a gaseous reactor determines in the final analysis the ultimate performance potential of these systems (Ref. 1). There are two physical processes which contribute: the nuclear radiation from the fission reactions, and the thermal radiation from the hot gas mixture in the cavities. Reliable estimates of the heat load on the solid from nuclear radiation are available and should suffice for preliminary studies of the gaseous reactor concept. The effect of thermal radiation, however, is not as well known, and further analysis and experimental information are required.

In the earlier studies of gaseous cavity reactors for propulsion (Refs. 1 and 2) the thermal radiation from the gas to the containing walls was estimated on the basis of the following assumptions: (1) the temperature of the gas mixture in the cavities is proportional to the enthalpy of the gas, and (2) the gas mixture is transparent and radiates to the walls at its maximum (central) temperature. It was recognized that this model would yield at best a first-order estimate. A more recent treatment of the problem reveals that the first assumption is too conservative and unnecessarily handicaps the system performance. A more realistic temperature–enthalpy relationship was therefore considered. The second assumption has been reviewed also, and a more flexible representation of the physical situation has been incorporated by introducing two limiting cases which are expected to bracket the actual radiative properties of the gas mixture.

II. TEMPERATURE–ENTHALPY RELATION

Inasmuch as hydrogen is the most attractive propellant for direct nuclear propulsion devices, it is appropriate to select a temperature–enthalpy relation which would be most descriptive for this material in the temperature range of interest. Enthalpies of pure hydrogen have been computed by a number of investigators. In this analysis the work of Altman (Ref. 3) is utilized. In Fig. 1 hydrogen gas stagnation (i.e., chamber) temperature is shown as a function of the square of the specific impulse which would be obtained if the gas were expanded through a nozzle with a chamber-to-exhaust pressure ratio of 10,000. These results are based on the assumption that the gas is at thermal equilibrium at each point in the expansion process. Since the specific impulse obtainable from a rocket nozzle is proportional to the square root of the enthalpy difference between the chamber and exhaust stations, the abscissa must be proportional to this enthalpy difference. For the systems to be considered here it is assumed for simplicity that the expansion is complete (Ref. 1); thus, the specific impulse for these systems will be proportional to the square root of the stagnation enthalpy, h_c, of the hydrogen in the reactor cavities. On this basis the abscissa of the graph may be further interpreted as h_c. The figure reveals, however, that $T_c(h_c)$ is not a simple function. A reasonable approximation to the functional relationship is seen to be

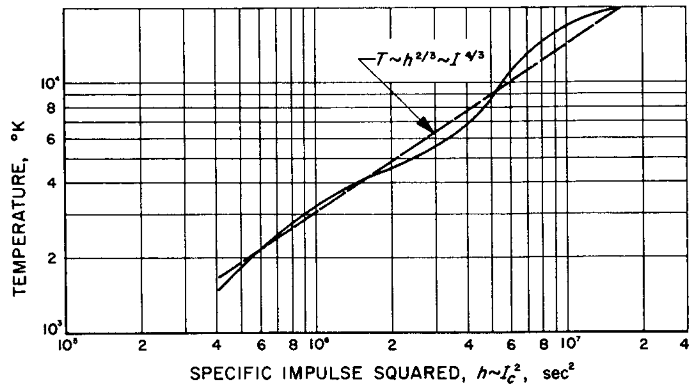

Figure 1. Temperature versus specific impulse squared for hydrogen with equilibrium flow

$$T_c(h_c) \sim h_c^{2/3} \tag{1}$$

(which is shown in the figure as a dashed straight line). This relationship will suffice for the present needs; certainly, it will yield an improvement over the linear dependency selected for the earlier studies.

III. THERMAL RADIATION FROM GAS MIXTURE IN CAVITIES

Without detailed knowledge of the composition, temperature distribution and densities of the gas mixture in the reactor cavities, it is, of course, impossible to determine precisely the thermal radiation flux at the solid boundaries. A first crude attempt to estimate the relative importance of this component of the heat load on the solid members of the reactor was based on the assumption that the gas mixture would be essentially transparent and would radiate to the walls at its central temperature. More recent detailed calculations of the emissivity of hydrogen under equilibrium conditions and pressures of around a hundred atmospheres indicate that although this may be a good assumption for the temperature range of 1,000 to 6,000°K, that in the range of 6,000 to 50,000°K, hydrogen emits for all practical purposes like a black body (Refs. 4 and 5). Actually the problem is even more complex because the presence of fissionable species, such as uranium and plutonium halides even at small concentrations, will most likely affect the radiative characteristics of the mixture.

Another complication even less well understood at this time is the role of the various metastable species produced in the mixture by the slowing down of the fission fragments. It is expected that these too will influence the radiative transfer phenomena. The futility of attempting a detailed treatment of the problem in the absence of experimental facts about the nuclear fuel carrier, the separation process and fission fragment physics, is therefore apparent.

In spite of these difficulties it is possible to extract some additional information about the thermal radiation heat load by bracketing the actual physical situation with two limiting cases. At one extreme the gas mixture in the cavity is considered to be entirely opaque, and at the other, essentially transparent. In the first case both the gas and the solid boundaries are assumed to radiate as black bodies, the effective radiating temperature of the gas being some intermediate value between the wall temperature and the central, maximum temperature of the gas in the cavity. In the transparent case, the gas mixture is taken to have a very low emissivity, zero opacity, and to radiate at its maximum temperature. In both cases a cylindrical cavity is selected for the analysis.

A. Opaque gas

When the gas mixture is opaque, the shape of its outer boundary does not enter into the analysis, and the system can be represented by a pair of infinite, flat surfaces. One surface is the gas, which is taken in general as a gray body with emissivity ε_c and radiating temperature T_g, and the other is the solid boundary with emissivity ε_s and temperature T_s. On this basis the net power radiated from the gas to the boundary P_{rg} is given by the well known relation (see for example, Ref. 6)

$$P_{rg} = \frac{\sigma A_c \varepsilon_c \varepsilon_s (T_g^4 - T_s^4)}{\varepsilon_s + \varepsilon_c (1 - \varepsilon_s)} \tag{2}$$

where σ is the Stephan-Boltzmann constant, and A_c is the surface area common to gas and wall. For simplicity it is further assumed that the two media have the same effective radiating areas. If, as specified above, $\varepsilon_c = \varepsilon_s = 1$ then Eq. 2 reduces to the form

$$P_{rg}^0 = \sigma A_c (T_g^4 - T_s^4) \tag{3}$$

This relation will be used for the opaque gas case, with a suitable specification of the effective gas temperature, T_g.

B. Transparent gas

For this case the actual geometry of the cavity wall must be considered. To obtain the net radiation passing from gas to wall, the difference between the total radiation incident upon the wall and that incident upon the gas is required. The radiation flux from the wall into the gas at the gas-wall interface is given by

$$Q_- = \sigma A_c \varepsilon_s T_s^4$$

The outward (gas-to-wall) directed flux consists of two components: that from the opposite walls and transmitted by the gas, and that from the gas itself; thus,

$$Q_+ = \sigma A_c (\varepsilon_c T_g^4 + \varepsilon_s \tau_s T_s^4)$$

where τ_s is the transmissivity of the gas to gray-body radiation from the wall at temperature T_s. If the reflectivity of the gas is ignored, then at thermal equilibrium,

$$\tau_s = 1 - \alpha_s \tag{4}$$

The symbol α_s denotes the absorptivity of the gas to radiation at T_s, and in this case is simply the emissivity ε_s.

If this expression is used in Q_+ then the net power radiated from gas to wall is given by

$$P_{rg} \equiv Q_+ - Q_- = \sigma A_c \varepsilon_c (T_g^4 - \varepsilon_s T_s^4) \tag{5}$$

For this analysis $\varepsilon_s = 1$; thus,

$$P_{rg}^{\infty} = \sigma A_c \varepsilon_c (T_g^4 - T_s^4) \tag{6}$$

which is the form to be used for the transparent gas case.

The effective gas temperature, T_g, is taken as some fraction of the difference, $T_c - T_s$, where T_c is the maximum (presumably central) temperature of the gas in the cavity. Thus in general there is a temperature rise in the gas starting at the wall value T_s; this is due, of course, to the gas-phase fission-heating in the cavities. In general,

$$T_g = T_s\left[\vartheta\left(\frac{T_c}{T_s} - 1\right) + 1\right] \qquad 0 \leqq \vartheta \leqq 1 \tag{7}$$

thus, for the opaque gas case Eq. 3 may be written

$$P_{rg}^{0} = \sigma A_c T_s^4 \left\{\left[\vartheta\left(\frac{T_c}{T_s} - 1\right) + 1\right]^4 - 1\right\} \tag{8}$$

In this situation the effective gas temperature will be that at a layer perhaps one mean-free-path inside the gas surface; thus $T_g \simeq T_s$, so that for this analysis $\vartheta = 0.1$ is used. This choice is not entirely arbitrary. Detailed analysis of the radiation exchange between two black surfaces separated by an absorbing gas indicate that for an optically thick gas region (two or more optical thicknesses) the effective gas temperature at the cold wall is in the order of 0.2 of the temperature difference between the two walls (Ref. 7). The value $\vartheta = 0.1$ should therefore be representative of the systems of interest.

In the case of a transparent gas $\vartheta = 1$ is assumed, as mentioned previously. Then Eq. 6 may be written:

$$P_{rg}^{\infty} = \sigma A_c \varepsilon_c T_s^4 \left[\left(\frac{T_c}{T_s}\right)^4 - 1\right] \tag{9}$$

This is in fact the form selected for the earlier treatment (Ref. 1).

It is of interest to compare the magnitude of these two expressions for the power radiated by the gas mixture in the cavities. If for this computation the temperature-enthalpy relation (Eq. 1) is used for both cavity and solid temperatures, then

$$\frac{P_{rg}^{\infty}}{P_{rg}^{0}} \equiv p_{rg}(h) = \frac{\varepsilon_c (h^{8/3} - 1)}{[\vartheta(h^{2/3} - 1) + 1]^4 - 1} \tag{10}$$

where

$$h \equiv \frac{h_c}{h_s} \tag{11}$$

In Fig. 2 the ratio p_{rg}/ε_c is shown as a function of the specific impulse ratio, $I = h^{1/2}$, for three different values

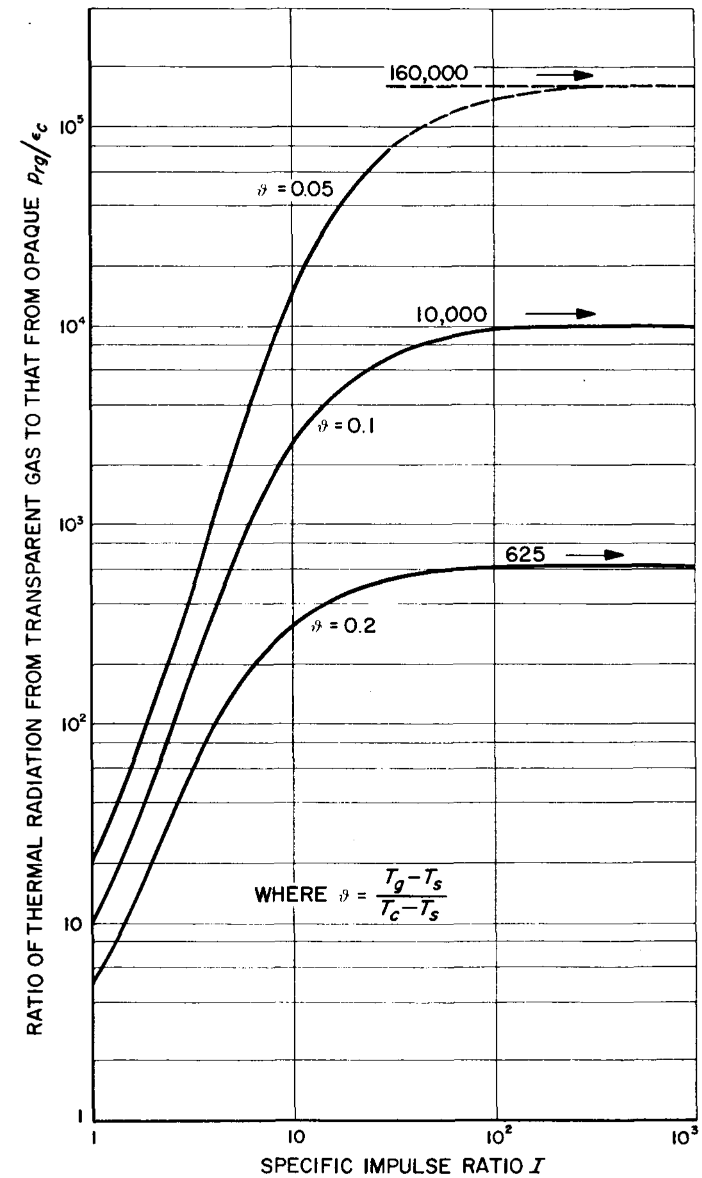

Figure 2. Comparison of thermal radiation from transparent and opaque hydrogen gas

of the parameter ϑ. It is seen from the figure that p_{rg}/ε_c approaches an asymptote as $I \rightarrow \infty$; this is,

$$\lim_{I \rightarrow \infty} \frac{p_{rg}}{\varepsilon_c} = \frac{1}{\vartheta^4} \tag{12}$$

At the other extreme, $I \rightarrow 1$, the limit is

$$\lim_{I \rightarrow 1} \frac{p_{rg}}{\varepsilon_c} = \frac{1}{\vartheta} \tag{13}$$

The significance of this comparison is that for emissivities of the transparent gas greater than about 10^{-3}, the thermal radiation for the transparent gas system is generally much larger than that from the opaque, at equal values of the specific impulse ratio. For example, it may be noted that even for modest values of I ($\simeq 2.5$) with $\varepsilon_c = 10^{-3}$, $p_{rg} \simeq 1$, while for $\varepsilon_c = 1$, $p_{rg} \simeq 100$. At very large I ($\rightarrow \infty$), $\varepsilon_c = 10^{-3}$ gives $p_{rg} \simeq 10$, and at $\varepsilon_c = 1$, $p_{rg} \simeq 10{,}000$. The practical implication of these observations is that for comparable gains in specific impulse, the transparent gas systems yield substantially larger engine weights than do the opaque. This point is discussed further in the next section, in which system performance is considered.

It should be borne in mind that these results are all based on the use of the value 0.1 for ϑ. Thus, although they would not be quantitatively valid for other ϑ, they do apply qualitatively.

IV. SPECIFIC IMPULSE CALCULATIONS

The influence of the thermal radiation from the gas mixture in the cavities on the specific impulse is determined by introducing the two forms for P_{rg} (Eq. 8 and 9) into an expression for the power balance in the nuclear engine. For this calculation the generalized engine model which incorporates a non-temperature limited region in the nuclear core and a radiator circuit to dispose of heat deposited in the engine solids is selected. On this basis it can be shown that an analysis of the power balance yields the result (Ref. 1)

$$\frac{h_c}{h_s} = \frac{1}{\mu}\left[1 + \gamma(1-\mu) - \frac{P_{rg}}{\dot{m}h_s}\right] \tag{14}$$

where

$$\gamma \equiv \frac{P_r}{\dot{m}h_s} \quad \text{and} \quad \mu \equiv f + \zeta(1-f), \tag{15}$$

P_r is the power rejected by the radiator, $\dot{m}$ is the mass flow rate of propellant, f is the fraction of fission power released in the temperature-limited (solid) region of the reactor, $1-f$, that in the non-temperature limited region, ζ is the fraction of energy from fission reactions which appears as nuclear radiation, and h_s is the propellant enthalpy per unit mass at the maximum allowable temperature of the solid T_s.

For analytical convenience T_s is identified with the solid-wall temperature previously specified in connection with Eq. 2. Then, the substitution of the two expressions for P_{rg} into the last term of Eq. 14 along with the temperature-enthalpy relation (Eq. 1), yields

$$\frac{P^0_{rg}}{\dot{m}h_s} = \beta_s\{[\vartheta(h^{2/3}-1)+1]^4 - 1\} \quad \text{with} \quad \beta_s \equiv \frac{\sigma A_c T_s^4}{\dot{m}h_s} \tag{16}$$

$$\frac{P^\infty_{rg}}{\dot{m}h_s} = \beta(h^{8/3}-1) \quad \text{with} \quad \beta \equiv \frac{\sigma\varepsilon_c A_c T_s^4}{\dot{m}h_s} \tag{17}$$

Again it is noted that the form of Eq. 17 is essentially the expression used in the earlier work (Ref. 1), except for the modification of the enthalpy relation. Furthermore, the thermal radiation parameter, β, is defined as before, although a new parameter, β_s, is introduced for the description of the opaque gas systems. (From these definitions it follows that the function plotted in Fig. 2 is in fact $p_{rg}\beta_s/\beta$.)

If these expressions are used in the power balance relation (Eq. 14), then the specific impulse ratio can be related to the principal engine parameters, μ, γ and β or β_s. The relationship between I and β (or β_s) for some representative values of f is shown in Fig. 3. These curves apply for the special case $\gamma = 0$ (i.e., no radiator), which as previously shown, corresponds to the high thrust engines (Ref. 2). Throughout, $\zeta = \vartheta = 0.1$ has been used. In Figs. 4 and 5, I is shown as a function of γ, for various β (or β_s) and f. These results apply to the high specific impulse (low thrust) engines (Ref. 1). A comparison of these results with the earlier work reveals a marked gain in specific impulse for given values of f, β and γ; this

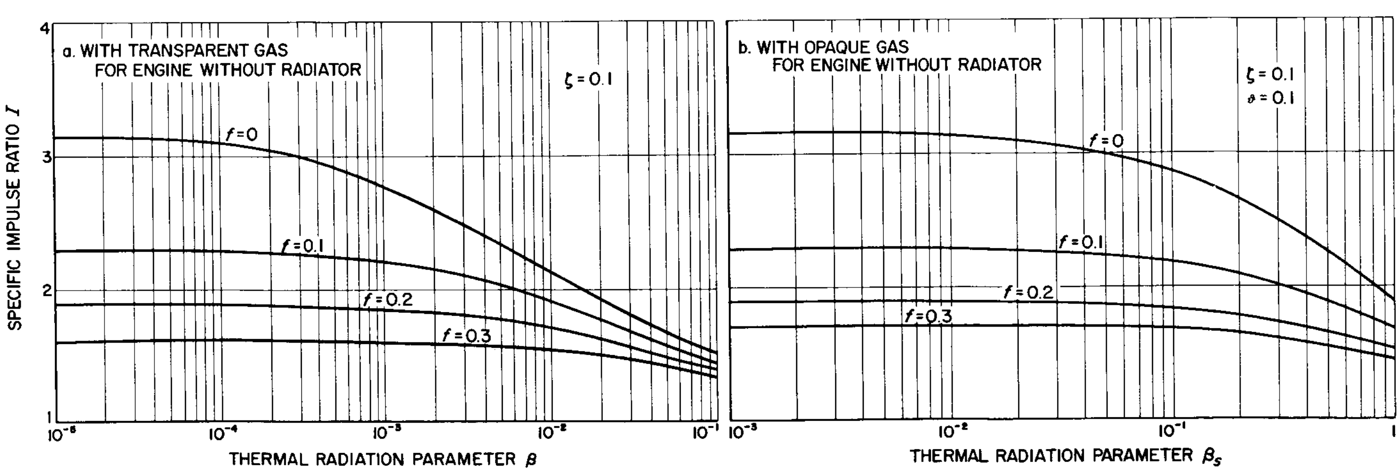

Figure 3. Specific impulse ratio for engine without radiator

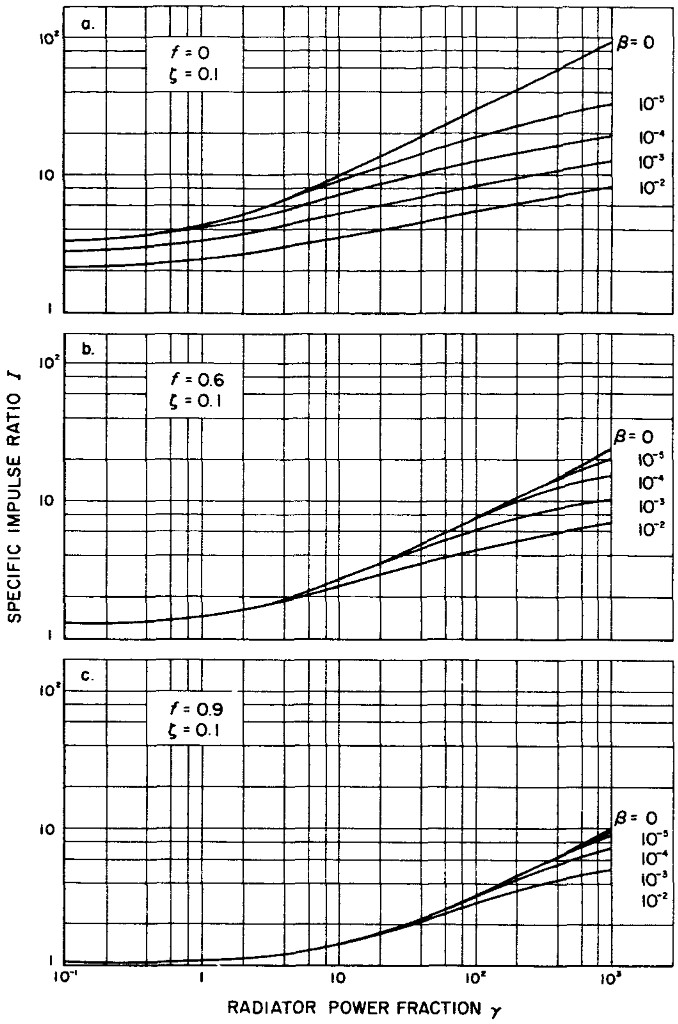

Figure 4. Specific impulse ratio as a function of radiator power fraction, for transparent gas

results, of course, from the improved temperature-enthalpy relation.

As mentioned earlier, the choice of the functional form for P_{rg} has a strong influence also on the engine characteristics and performance. Consider first the case of the engine-without-radiator ($\gamma = 0$). It is convenient to examine the effect of P_{rg} on these systems by comparing the values of the solid fission fraction, f, to yield a given specific impulse with the two forms (Eq. 16 and 17). The comparison is drawn for a selected pair of parameters β_s and ϵ_c. For this purpose the functions (*cf.* Eq. 14)

$$f_\infty = \frac{\zeta}{1-\zeta}\left\{\frac{1}{I^2\zeta}\left[1 - \epsilon_c\beta_s\left(I^{16/3} - 1\right)\right] - 1\right\} \tag{18}$$

$$f_0 = \frac{\zeta}{1-\zeta}\left\{\frac{1}{I^2\zeta}\left[1 - \frac{\beta_s\left(I^{16/3} - 1\right)}{R\,(I)}\right] - 1\right\} \tag{19}$$

are introduced, where f_∞ denotes the solid fission fraction for the system with transparent gas, and f_0, that for the system with opaque. The function $R(I) \equiv p_{rg}\,(I)/\epsilon_c$, is simply the quantity shown in Fig. 2. Given, then the pair, β_s and ϵ_c, one can compare f_∞ and f_0 for various I. Some representative cases are shown in Fig. 6. The principal conclusion to be drawn from these results is that in general $f_\infty \simeq f_0$ for $1 \leqq I \leqq \zeta^{-1/2}$, the maximum performance range possible with a regeneratively cooled engine. The physical interpretation is that in these systems the thermal radiation heat load on the solid members of the engine is but a small part of the total energy attenuated, and the functional form of P_{rg} has little effect on the system performance. Thus, in a sense, the regeneratively cooled engines are relatively low-performance devices, and the thermal radiation from the fissioning gas mixture is not a major factor in the power balance

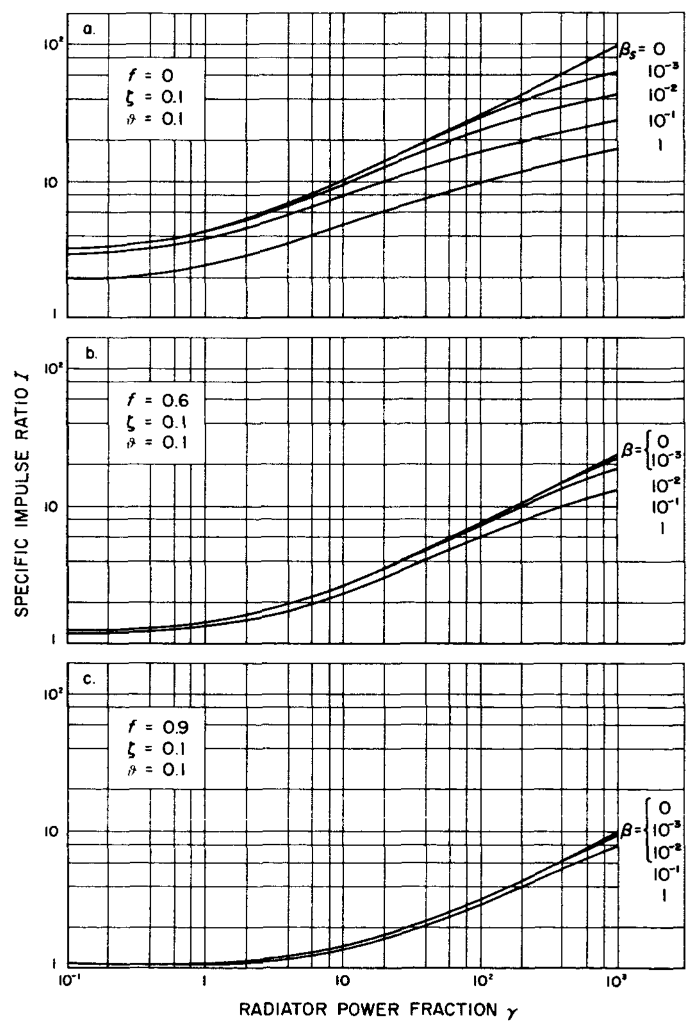

Figure 5. Specific impulse ratio as a function of radiator power fraction, for opaque gas

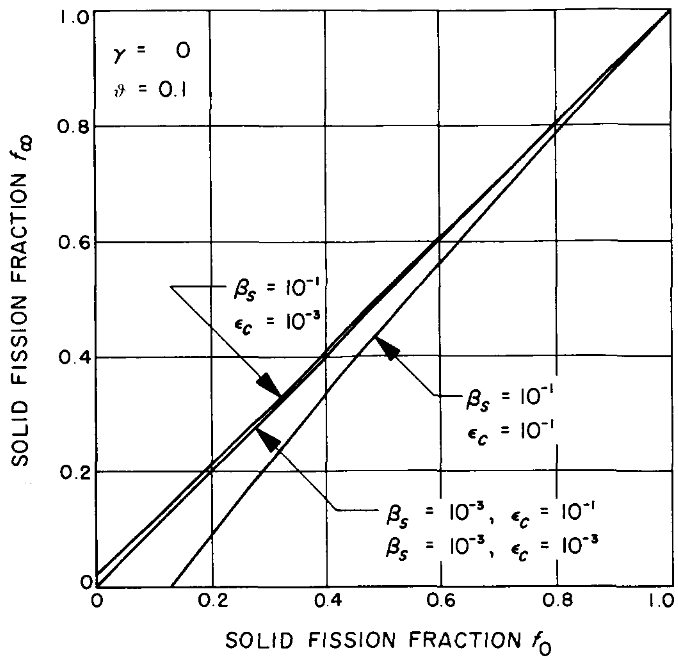

Figure 6. Comparison of solid fission fractions for transparent and opaque gas systems

(Ref. 8). The only exceptions to this rule arise when $\beta = \beta_s\,\varepsilon_c$ becomes large (see for example the lower curve in Fig. 6). In these cases the emissivity from the transparent gas is relatively large, and the total thermal radiation from the gas is comparable to the regenerative cooling capacity of the engine (note the definition of β_s). Under these circumstances the performance of the transparent gas systems is less than that of the opaque. Thus, if the performance of the two systems is required to be the same, then the transparent gas system, because of its greater radiation loss rate, must be operated at a smaller value of f; i.e., a larger fraction of the nuclear fuel must be in gas phase (Ref. 2).

The influence of P_{rg} on engine performance is more striking in the systems-with-radiator ($\gamma > 0$). For these the comparison is made on the basis of the radiator power fraction, γ. Thus, given the radiation parameters ε_c and β_s and the solid fission fraction f, the ratio γ_∞/γ_0 is determined such that two systems, one with a transparent gas and the other with an opaque, produce the same specific impulse. The functional form of γ_∞/γ_0 is easily shown from Eqs. 14 through 17 and definition 10, to be

$$\frac{\gamma_\infty}{\gamma_0} = 1 + \frac{p_{rg}(I) - 1}{1 + \mu I^2 p_{rg}(I)/\varepsilon_c \beta_s (I^{16/3} - 1)} \qquad (20)$$

This ratio is shown in Fig. 7 as a function of I for $f = 0$ and various combinations of ε_c and β_s. The lower limit of γ_∞/γ_0 is unity, as $I \to 1$. For large values of I [such that $\mu\, p_{rg}(I) << \varepsilon_c\,\beta_s\,I^{10/3}$],

$$\frac{\gamma_\infty}{\gamma_0} \sim p_{rg}(I) \qquad (21)$$

As noted previously in the discussion of the function $p_{rg}(I)$, at the larger values of I (greater than 6), the transparent gas systems impose the greater heat load on the engine solids; consequently the radiator power fraction [and therefore radiator size and weight (Ref. 1)] for these may be orders of magnitude greater than that for the opaque gas systems. Below $I = 6$, the comparison is not so clear-cut except when the transparent gas emissivity is relatively large (approximately 10^{-1}). It is seen from Fig. 7 that for these systems, γ_∞/γ_0 is generally much greater than unity. For smaller values of ε_c, $\gamma_\infty/\gamma_0 \simeq 1$, so long as $\beta_s < 10^{-1}$. When $\beta_s > 10^{-1}$, γ_∞/γ_0 may become significantly less than unity. As already

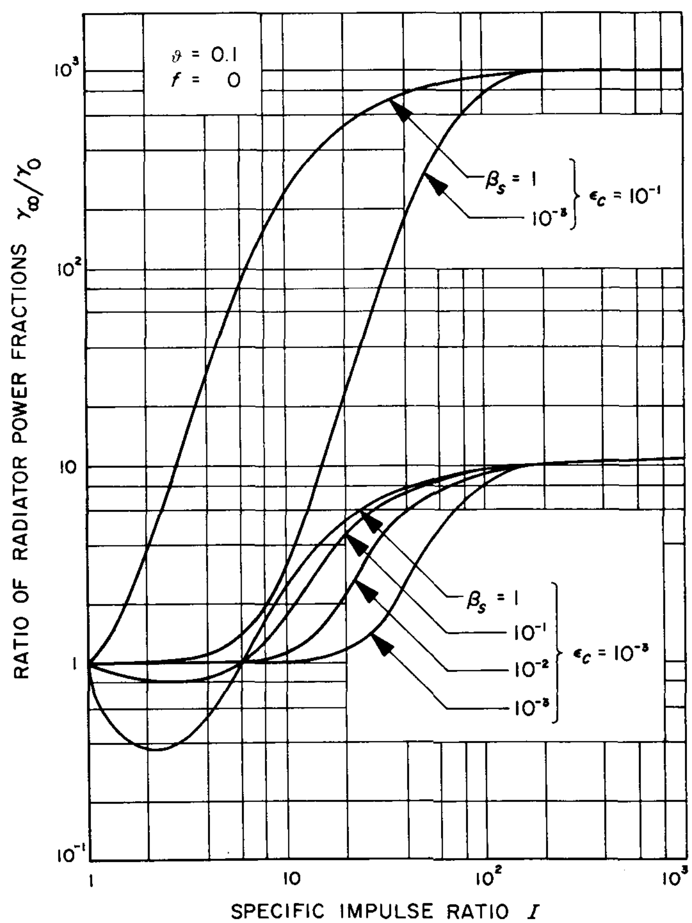

Figure 7. Ratio of radiator power fractions to obtain same specific impulse for transparent and opaque gases

noted, from the analysis of the systems-without-radiator, this means that the thermal radiation from the opaque gas is a sizeable fraction of the regenerative cooling capacity, and if ε_c is very small, situations will arise wherein the radiation from the transparent gas will be less than that from the opaque; thus $\gamma_\infty/\gamma_0 < 1$.

V. CONCLUSIONS

(1) In systems-without-radiator, the functional form of the thermal radiation term (i.e., the choice between an opaque and a transparent gas) is not an essential factor in determining engine performance. In these systems, the thermal radiation term is generally a small part of the overall power balance (i.e., $\beta_s < 10^{-1}$) and therefore has but a secondary effect on the specific impulse. Only when $\beta_s > 10^{-1}$, does thermal radiation play a significant role. In that event, the question about the transparency of the gas mixture is an important consideration. This question was examined here in terms of its influence on the solid fission fraction.

(2) In systems-with-radiator, the transparent gas requires considerably larger radiators than the opaque, when the specific impulse ratio is greater than about 6. This conclusion is generally valid. Its practical significance is that if experiment shows the gaseous mixture of fissionable material and propellant to be essentially transparent, then the radiator must be quite large in order to dispose of the radiation heat load on the engine solids. This in turn will result in high engine specific weights. As noted in an earlier study (Ref. 7), such systems could not compete favorably with other low-thrust engines, such as the nuclear-electric, on the more difficult planetary missions.

(3) When the specific impulse ratio is less than 6 and the transparent gas emissivity large ($\varepsilon_c > 10^{-1}$), the transparent gas systems require the larger radiators.

(4) When the specific impulse ratio is less than 6 and the transparent gas emissivity small ($\varepsilon_c \sim 10^{-3}$), the radiator requirements are comparable, so long as $\beta_s \leq 10^{-1}$. At greater values of β_s, the opaque gas system will require the larger radiator, and hence yield the higher engine specific weight.

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